

Ultra-Compact Dwarf Galaxies in the Fornax Cluster ¹

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ABSTRACT

By utilising the large multi-plexing advantage of the 2dF spectrograph on the Anglo-Australian Telescope, we have been able to obtain a complete spectroscopic sample of all objects in a predefined magnitude range, $16.5 < b_j < 19.7$, regardless of morphology, in an area towards the centre of the Fornax Cluster of galaxies. Among the unresolved or marginally resolved targets we have found five objects which are actually at the redshift of the Fornax Cluster, i.e. they are extremely compact dwarf galaxies or extremely large star clusters. All five have absorption line spectra. With intrinsic sizes less than $1.1''$ HWHM (corresponding to approximately 100pc at the distance of the cluster), they are more compact and significantly less luminous than other known compact dwarf galaxies, yet much brighter than any globular cluster. In this letter we present new ground based optical observations of these enigmatic objects. In addition to having extremely high central surface brightnesses, these objects show no evidence of any surrounding low surface brightness envelopes down to much fainter limits than is the case for, e.g., nucleated dwarf ellipticals. Thus, if they are not merely the stripped remains of some other type of galaxy, then they appear to have properties unlike any previously known type of stellar system.

Subject headings: galaxies: clusters: individual: Fornax — galaxies: compact — galaxies: photometry — galaxies: fundamental parameters

1. Introduction

Almost since the beginning of extra-galactic astronomy it has commonly been assumed that

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the full range of galaxy types and sizes is already known and catalogued, essentially a ‘what you see is what you get’ (WYSIWYG) point of view. Nevertheless, less conventional views have still been espoused (e.g. Zwicky 1957, Arp 1963, Disney 1976). These might perhaps be termed WYGIWYS, ‘what you get is what you see’, as they posit that selection effects have biased you against seeing anything else. Observation has indeed provided new types of galaxy from time to time. Shapley’s (1938) discovery of extremely low luminosity dwarf spheroidals in the Local Group (see also Shapley 1943), the discovery by Zwicky (1957) himself of blue compact galaxies, and in more recent years the finding of ever lower surface brightness galaxies (Impey, Bothun & Malin 1988), including some of remarkably large size (Bothun et al. 1987), have all extended our view of the overall galaxy population.

Even so, the currently standard view has galaxies, or stellar systems in general, occupying discrete regions of the possible continuum of size or luminosity versus surface brightness. Giant ellipticals have high luminosities and high central surface brightnesses, the latter declining somewhat towards the most luminous objects (Kormendy 1977). Dwarf ellipticals and dwarf spheroidals run from moderate luminosity and moderate surface brightness down to low values of both parameters (Ferguson & Binggeli 1994). Disc galaxies similarly have lower surface brightnesses at lower luminosities (and later types), running into irregular galaxies at the faint end (Binggeli, Sandage & Tammann 1984). Finally globular clusters have luminosities not much less than a dwarf galaxy, but are very much smaller (more compact), so have very high central surface brightnesses (Djorgovski 1995). The current situation can be summarised schematically in a ‘Kormendy diagram’ as in figure 1 (following Ferguson & Binggeli 1994). There are some known exceptions to the general rule. M32 is of significantly higher surface brightness than other dwarf (and most giant) ellipticals, but may be either on the (very sparse) extension of the ‘normal’ elliptical sequence to much lower luminosities or a pathological case caused by tidal stripping of a formerly larger system by the nearby M31 (Faber 1973). NGC 4486B in Virgo may be another reasonably similar galaxy, but M32-like dwarfs appear conspicuous by their absence in clusters such

as Fornax (Drinkwater & Gregg 1998). Similarly Malin 1 is an extreme low surface brightness disc galaxy of huge size, but even the so called ‘Malin 1 cousins’ are almost an order of magnitude smaller.

In the present paper we discuss the existence of what may be, if they are not merely the remnants of some interaction, a new *class* of galaxy, as opposed to exceptional cases. In the course of a complete spectroscopic survey of the Fornax Cluster (Drinkwater et al. 2000a = Paper I) we have found several examples of extremely compact, yet moderately luminous galaxies (Drinkwater et al. 2000b = Paper III; Drinkwater et al. 2000c), which occupy a hitherto empty region of the surface brightness – size (luminosity) plane. We discuss the spectroscopic discovery and the optical photometric properties of these objects in the following sections 2 and 3, examining in particular whether they could be the tail (to high surface brightness and/or low luminosity) of known galaxy types. Possible origins for these systems are explored in section 4.

2. The Fornax Cluster Spectroscopic Survey

With the advent of modern multi-object spectroscopic facilities, exemplified by the ‘two-degree field’, or 2dF, spectrograph on the Anglo-Australian Telescope (Taylor, Cannon & Parker 1998), entirely new ways of surveying the universe have become possible. We have taken advantage of these opportunities by carrying out the first deep, all-object survey of a galaxy cluster region. That is, we have obtained spectra for all the objects in the region between set magnitude limits, regardless of apparent morphology (i.e. ‘star’ or ‘galaxy’). One of the main reasons behind this strategy was to test the hypothesis that compact, high surface brightness galaxies have been ignored in conventional galaxy surveys because of their small isophotal size or, indeed, because they are indistinguishable from stars in the ordinary ground-based imaging which provides the input catalogues for galaxy spectroscopic surveys (e.g. Disney & Phillipps 1983).

The system we use, 2dF on the AAT, has two sets of 200 fibres, each feeding a separate spectrograph and allowing the simultaneous observation of 400 objects. In the central 2 degree diameter

area of the Fornax Cluster there are around 4000 objects in the chosen magnitude range $16.5 \leq b_j \leq 19.7$ for galaxies, $16.5 \leq b_j \leq 20.0$ for ‘stars’, thus requiring at least 10 separate observations. Of course, even towards the cluster centre, the majority of objects are not cluster galaxies, the numbers being dominated by foreground Galactic stars and background field galaxies (Paper I). We used the 300B grating, giving wavelength resolution of approximately 9 \AA (4.3 \AA per pixel) over the range 3600 - 8100 \AA , the same set-up as for the general 2dF Galaxy Redshift Survey (e.g. Folkes et al. 1999). Total integration times (the observations are usually subdivided to assist with cosmic ray removal) ranged from 1 hour for the brighter, higher surface brightness objects to about 3 hours for the fainter low surface brightness galaxies.

The overall input catalogue for the survey is derived from Automated Plate Measuring (APM) machine scans of UK Schmidt Telescope plates of the area (see Irwin, Maddox & McMahon 1994). The APM catalogue lists positions, magnitudes and morphological classifications (‘star’ = unresolved, ‘galaxy’ = resolved, or ‘merged’ = overlapping images, usually of a star and a fainter galaxy). The APM magnitudes of unresolved images are internally calibrated, but we also checked them using our own CCD photometry from the CTIO Curtis Schmidt (see Paper I), resulting in a small zero point adjustment compared to the default APM magnitudes. Magnitudes for resolved galaxy images were derived as discussed in Paper I. We then chose to target spectroscopically all objects with magnitudes $16.5 \leq b_j \leq 19.7$, (or 20.0 for stars) where b_j is the natural UKST photographic B band defined by the IIIaJ emulsion and GG395 filter (see e.g. Blair & Gilmore 1982).

The spectra were reduced using both DOFIBERS within IRAF² and the instrument specific 2dFDR software, with essentially identical results. No attempt is made to ‘flux’ the spectra. Further particulars, especially on the sky subtraction, are given in Paper I and we do not repeat them here.

Once we have reduced spectra, we determine redshifts and approximate spectral types uniformly for all objects in the survey via the cross-

correlation method (Tonry & Davies 1979). All the object spectra (irrespective of image classification) are compared with a set of standard templates; nine stellar templates for types A3V through M5V from Jacoby, Hunter & Christian (1984) plus emission line galaxy and QSO templates. Note that the stellar templates result in equally good correlations for absorption line galaxies as would actual galaxy templates (see Paper I). Cross-correlations are calculated using RVSAO (Kurtz & Mink 1998), which determines a redshift (cz), its error, and the Tonry-Davis R coefficient which measures the significance of the match. We accept only identifications with $R > 3$ and in addition check by eye for any possible misidentifications. The rms velocity error found from repeat observations is $\simeq 64 \text{ km s}^{-1}$, consistent with the values reported by RVSAO and with external comparisons (primarily with Hilker et al. 1999b).

As of the end of 1999, we had observed 92% of our targets in the desired magnitude range in a 2 degree diameter field in the centre of the cluster (centred close to NGC 1399) and successfully obtained redshifts for 94% of those. The results show the Fornax Cluster to be well separated from the rest of the field in redshift space. From our 2dF results alone (which correspond to dwarf galaxies with $-15.0 \leq M_B \leq -11.5$) we find a cluster redshift $cz_{mean} = 1450 \pm 70 \text{ km s}^{-1}$ and a velocity dispersion $\sigma = 380 \pm 50 \text{ km s}^{-1}$, in good agreement with the values for brighter galaxies (e.g. Jones & Jones 1980). There are no galaxies with $cz < 900$ or between 2300 and 3000 km s^{-1} .

3. Cluster Compact Galaxies

From the reduced spectra it is clear that a small but not insignificant fraction of the ‘stars’ actually have galaxy spectra with recession velocities greater than 1000 km s^{-1} . A number of these are fairly distant compact emission line galaxies (see Drinkwater et al. 1999 = Paper II), while a few are similarly distant compact galaxies but with absorption line spectra. In addition, as reported in Paper III, four unresolved objects and a fifth marginally resolved object turn out to have velocities clearly indicating membership of the Fornax Cluster. Even without further analysis, their lack of obvious resolution on UKST

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survey plates already marks them down as unusual objects, since at an assumed Fornax distance of 20 Mpc (distance modulus 31.5; Drinkwater, Gregg & Colless 2001), a scale-length of $1''$, say, would correspond to just 100pc. The five objects – to which we attach the provisional classification ultra-compact dwarf or UCD – are listed in Table 1. Images/finding charts are provided in Paper III.

Note that the existence of these five UCDs increases the known number of cluster dwarfs in the relevant magnitude range by about 10% if we take the number of ‘certain’ members seen in our area at slightly brighter magnitudes in Ferguson’s (1989) Fornax Cluster Catalog (FCC) and extrapolate using Ferguson & Sandage’s (1988 = FS) cluster dwarf luminosity function. (Our own sample is too limited by the surface brightness limit for successful spectroscopic observations to define total numbers). The UCDs themselves are *not* in the FCC (even as background galaxies), presumably because they are still unresolved even on the much higher resolution Las Campanas plates used by FS. We also note, for later reference, that *all* the dwarf cluster members which were identified by FS are clearly visible (and well resolved) on our UKST plate and film material.

The two brightest of the ultra-compact (UCD3 and UCD4) turn out to have been observed independently by Hilker et al. (1999b; see table 1), who obtained spectra for some 50 objects down to $V = 20$ very close to the central cluster galaxy NGC 1399. They found them to be slightly resolved in their imaging data, and we see similar resolution of UCD3 in our CTIO CCD imaging and in R band Tech Pan photographic films from the UKST (which have slightly better resolution than the J plates used in the APM catalogue). The other four ultra-compact objects appear entirely stellar in all our ground based images, see figure 2.

The FWHM of the seeing on the Tech Pan data is about $2.3''$ while UCD3, the largest object, has an image FWHM around $3.2''$. A very simple deconvolution then suggests an intrinsic radius (HWHM) of about $1.1''$ or 110pc. Obviously the other UCDs must be smaller still. Note that at the distance of Fornax, even the physically smallest Local Group dwarf spheroidal, Leo II ($M_V \simeq -10.1$, effective radius 180pc; Mateo 1998), would be reasonably well resolved with an

intrinsic half-light radius of $2''$. The one relatively high surface brightness Local Group dwarf spheroidal, Leo I ($M_V \simeq -11.5$), would be even better resolved with effective radius around $3''$ (van den Bergh 1999).

The UCDs have absolute magnitudes within the range $-14.0 < M_B < -11.5$, placing them in the lower range of luminosities for known dwarf systems (Mateo 1998) as shown in figure 3. However, previously known low luminosity dwarfs have low surface brightnesses too, so are morphologically quite distinct from the present group of galaxies (see figure 1, where the UCDs are shown as the upward pointing arrows, since we have only lower limits to their true unconvolved central surface brightnesses). Put the other way round, our objects are much fainter than previously discovered nearby compact (high surface brightness) galaxies (e.g. those of Drinkwater & Gregg 1998; see also Drinkwater & Hardy 1991 for blue compact dwarfs). They are also very much fainter and smaller than the compact star-forming dwarfs seen at intermediate to high redshift (e.g. Guzman et al. 1998, Paper II) and do not appear to have any direct relationship to them.

On the other hand, the UCDs are much brighter than any Galactic globular clusters or known globulars around NGC 1399 (Bridges, Hanes & Harris 1991). The slightly resolved UCD3 is, of course, also considerably larger than any known globular (which have half light radii up to about 10pc; Djorgovski 1995). A third class of small stellar system which might be comparable to our objects are the M32-like dwarf ellipticals, but none of the candidates for such a galaxy listed in the FCC has yet been found to be a cluster member (Drinkwater & Gregg 1998). Finally, there are the nuclei of nucleated dwarf ellipticals. These dE,N nuclei do span the luminosity range of our ultra-compact (Binggeli & Cameron 1991), see figure 3, and are, of course, also very small. However, our UCDs can not be the nuclei of ‘ordinary’ dE,N as we would be able to see the surrounding dE itself (recall that we can detect and resolve all the FS dEs and dE,Ns in our area).

To examine whether our objects could be nuclei of very low surface brightness dEs, we have further analysed our Tech Pan R images of the five UCDs, and also new AAT prime focus CCD images ($0.23''$ pixels) for the two brightest ob-

jects (20 minute B band and 10 minute V band exposures obtained in service time with approximately $1.4''$ seeing), to look for any remaining diffuse surrounding starlight. None is detected in the CCD images down to 3σ surface brightness limits around $26.6V$ mags arcsec $^{-2}$ on scales of a few hundred parsecs. Similarly for the deep Tech Pan imaging, we see no sign of any surrounding envelope for any of the UCDs. (We do confirm that UCD3 is resolved, as previously suspected, but even there see no measurable light outside the central core). For UCD1, the faintness of the core and the absence of nearby objects allows us to determine an even lower limit of $27.1R$ mags arcsec $^{-2}$ on similar scales (the $4''$ to $6''$ range in the profiles shown in figure 2).

These limits are very much lower than seen for known dE,N galaxies. In particular, if we carry out exactly the same experiment for *all* 59 of the known FS dE,N galaxies in the area covered by our photometry, down to the lowest known luminosity objects of this type, we can easily measure the mean surface brightness for each. We find that they all have surface brightnesses 1 to 4 magnitudes higher than our 3 sigma upper limits on any surrounding galaxy to our UCDs. Thus if our objects are the nuclei of dEs, then they are dEs of unprecedented faintness, well separated from the known population, *or* the surrounding galaxy is no longer present, for example having been tidally stripped (see section 4).

Spectroscopically the UCDs look similar to ordinary early type dwarfs in the FCSS sample (see figure 3 of paper III), with no discernable emission lines. The template matching suggests slight differences, with K-type spectra consistent with old metal rich stellar populations, for the ultra-compact, compared to generally younger F or G-type populations in dEs and dE,Ns. This may argue for stellar populations in the ultra-compact rather like those in giant ellipticals in the cluster, which appear to be uniformly old and of high metallicity (Kuntschner & Davies 1998). Both metal rich globular clusters and M32 also have this type of spectrum (Hilker et al. 1999b). (Note that Hilker et al. suggest that their CGF5-4 (our UCD4) may differ from this (specifically from CGF1-4 = UCD3), in having a spectrum more like a metal poor globular or a dE nucleus, but we see no significant difference in our 2dF spectra).

4. Discussion and Summary

As intimated in the introduction, a potentially major shortcoming of morphology based catalogues of dwarf galaxies in clusters has been the possibility that only subsets of cluster members with familiar properties are selected. Specifically, high surface brightness dwarf galaxies may be mistaken for background giants, or indeed be so compact as to look like stars. Our all-object spectroscopic survey has shown that this is indeed the case. Very compact, small scale size, high surface brightness dwarfs do exist in clusters. The less extreme objects (Drinkwater & Gregg 1998; Drinkwater et al. 2000c) are probably an extension of classically identified dwarfs to rather higher surface brightness at a given magnitude, thus blurring somewhat the surface brightness - luminosity relation. We discuss the significance of these elsewhere. However, the group of objects identified by Drinkwater et al. (2000b,c), which were previously confused with stars, appear to be disjoint from any other known type of stellar system in the surface brightness - luminosity plane (figure 1).

Several possibilities as to their nature suggest themselves. They may be genuine (i.e. primordial) high central density galaxies, that is a new class of stellar system not previously identified; they may be super-massive versions of globular clusters; they may be the nuclei of extremely low surface brightness dE galaxies; or they may be tidally distorted remnants of normal dwarfs, either small M32-like objects or the nuclei of former nucleated dwarfs or late type spirals.

Relatively little can be said for or against the notion that the UCDs are smaller versions of M32, since the evolution of M32 itself is not clear (see van den Bergh 1999). We can note the lack of actual (i.e. moderate luminosity) M32 analogues in Fornax (Drinkwater & Gregg 1998), but of course some sort of post-formation tidal limiting effect may be more damaging to less massive systems. Similarly it is impossible to discount totally the possibility that the UCDs are really the nuclei of larger galaxies, though in this case their hosts would have to have surface brightnesses far below those of known dE galaxies (and so would still represent a class of galaxy disjoint in their properties from those already known).

If the UCDs are produced in the original galaxy formation process, it is possible that they are some sort of super-massive star cluster, perhaps a kind of globular cluster, rather than a ‘real’ galaxy (though one might argue that this is a merely semantic distinction). NGC 1399 is well known to have a large population of globulars (Grillmair et al. 1994). The UCDs are all situated within $30'$ (150 kpc) of NGC 1399, though of course our survey field has only twice this radius and some of the ultra-compact are actually nearer to other large galaxies, in projection, than to NGC 1399. (UCD3 is very close to NGC 1404 for example). Kissler-Pattig et al. (1999) have suggested that some of the globulars follow the dynamics of the cluster as a whole, rather than the halo of NGC 1399 itself, and that these may have been tidally removed from other cluster galaxies (see also West et al. 1995). Alternatively, West et al. also consider the possibility that intra-cluster globulars might form *in situ*. Of course, our objects are a factor 10 more luminous than any known globulars, so they would have to be massive ‘super-globulars’ if they were associated with such a population (see also Goudfrooij et al. 2000). Note that the radial distribution of the UCDs is consistent with that suggested by West et al. for an intra-cluster population but significantly more dispersed than the NGC 1399 globular cluster system discussed by Grillmair et al. (see Paper III).

Bassino et al. (1994) have discussed whether some, at least, of the globular clusters in rich systems, such as that of NGC 1399, could be the remnant nuclei of former nucleated dwarf ellipticals which have been accreted by the central cluster galaxy (NGC 1399 has cD galaxy like properties). They also note that remnants an order of magnitude more massive than normal globulars should also be formed by this process. This would be consistent with the luminosities of our objects as shown in figure 3. This possibility has recently been considered in more detail by Bekki, Couch & Drinkwater (2001). Alternatively, it may be possible that similar remnants can form from the ‘shredding’ by tidal forces of late type spirals with small nuclear bulges (Moore et al. 1996), since galaxies like M33 appear to have ‘bulges’ more akin to a giant star cluster (e.g. Mighell & Rich 1995).

Simulations suggest that in either version of this

remnant picture we might still expect to see surrounding very low surface brightness halos of stars, at least for several Gyr, but as noted above, none have yet been detected down to quite faint limits. On the other hand, the disrupted material, including surviving nuclei, would be expected to be more concentrated to the cluster centre than the galaxies as a whole (White 1987), as is observed (see Paper III).

Finally there is the possibility that the UCDs represent a genuinely new class of galaxy. In the cold dark matter (CDM) picture of galaxy formation (e.g. Kauffmann, Nusser & Steinmetz 1997), small dense halos should collapse at high redshifts and subsequently merge into larger structures. Recent simulations (e.g. Moore et al. 1998) have the resolution to begin to see the details of the evolution of small halos within larger cluster sized structures. However, the available resolution still limits investigation to masses $\sim 10^9 M_\odot$ and we do not yet know the lower mass limit for individual halos in a cluster environment, nor indeed, the behavior of the baryonic (visible galaxy) component within these sub-structures. Establishing some limits on low mass but dense galaxies could provide interesting future constraints on these models, providing the systems we are seeing are (within) primordial halos. Previously known very low mass galaxies are of low surface brightness (low visible baryonic surface density) and probably dark matter dominated throughout (Carignan & Freeman 1988; Mateo 1998), so high surface brightness dwarfs may provide interesting counter-examples. (It may be hard to see, for example, why they are so compact optically if they have dark matter core radii of several hundred parsecs like ‘normal’ dwarfs, or if the central dark matter density is similar for all dwarfs).

In summary, the observations to date do seem to suggest that we are seeing a new type of stellar system. The UCDs are certainly much more luminous than normal globular clusters but are at the same time much less luminous than known compact dwarf galaxies. They do have luminosities similar to known faint dwarfs (e.g. in the Local Group), but have entirely different morphologies, previously known extreme dwarfs all having low surface brightnesses. There remains the possibility that they are the remnants of some more well known type of galaxy, after disruption in the po-

tential of the cluster. In particular they share a common luminosity range with the nuclei of nucleated dwarf ellipticals, though no surrounding ‘host’ or the remains thereof is visible. Further observations at much higher resolution, both spatial and spectroscopic, are required in order to elucidate the true nature of these enigmatic objects. HST images and VLT spectra have recently been obtained for this purpose.

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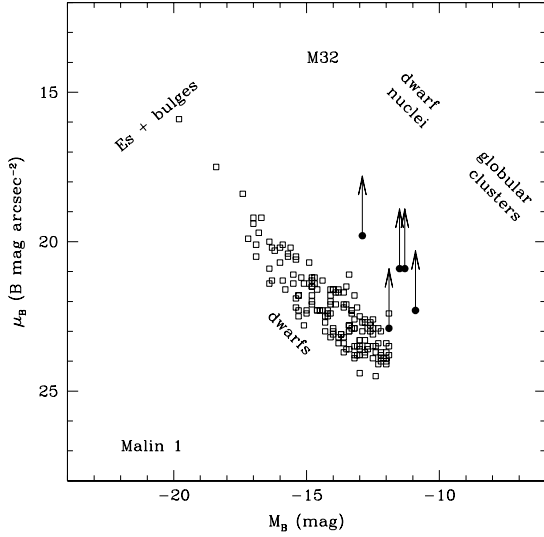


Fig. 1.— The absolute magnitude – central surface brightness plane for stellar systems and sub-systems. The squares indicate our measurements of dwarf galaxies in the Fornax Cluster and the filled circles the new Fornax compact objects (the surface brightness estimates are lower limits). The positions of other populations are from Ferguson & Binggeli (1994).

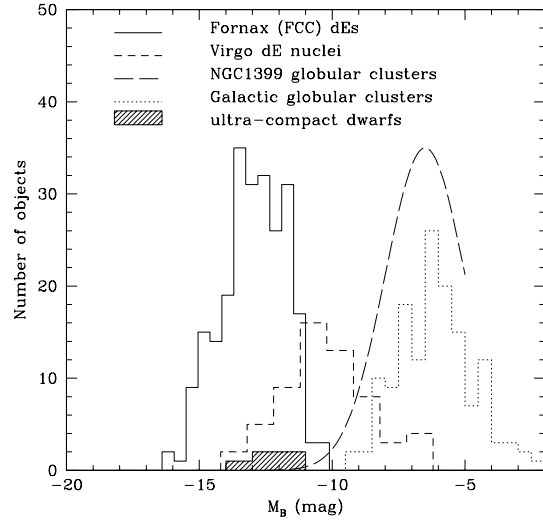


Fig. 3.— The distribution of absolute magnitude of the compact objects (filled histogram) compared to dEs in the Fornax Cluster (FCC; solid histogram), nuclei of dE,Ns in the Virgo Cluster (Binggeli & Cameron 1991; short dashes), a model fit to the globular clusters around NGC 1399 (Bridges et al. 1991; long dashes) and Galactic globular clusters (Harris 1996; dotted). The magnitude limit of our survey corresponds to $M_B = -11.5$.

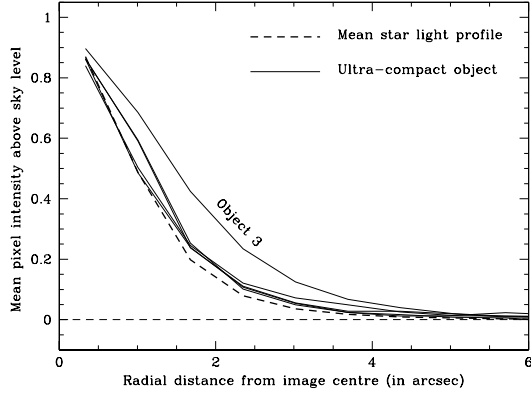


Fig. 2.— Radial R band intensity profiles (normalised to unity at the centre) for the five UCDs (thin lines) as derived from SuperCOSMOS scans of UKST Tech Pan films. For comparison the thick dashed line shows the average profile of neighbouring stars of similar magnitude.

Name	IAU Name	RA (J2000) Dec	b_j (mag)	M_B (mag)	cz (kms^{-1})	Hilker Name
UCD1	FCSS J033703.3-353804	03 37 03.30 −35 38 04.6	19.85	−11.6	1507	
UCD2	FCSS J033806.3-352858	03 38 06.33 −35 28 58.8	18.85	−12.6	1328	
UCD3	FCSS J033854.1-353333	03 38 54.10 −35 33 33.6	17.68	−13.8	1595	CGF1-4
UCD4	FCSS J033935.9-352824	03 39 35.95 −35 28 24.5	18.82	−12.7	1936	CGF5-4
UCD5	FCSS J033952.5-350424	03 39 52.58 −35 04 24.1	19.66	−11.8	1337	

Table 1: The Ultra-Compact Dwarfs